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Random telegraph noise in metallic single-walled carbon nanotubes

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We have investigated random telegraph noise (RTN) observed in individual metallic carbon nanotubes (CNTs). Mean lifetimes in high- and low-current states, τ_{high} and τ_{low}, have been studied as a function of bias-voltage and gate-voltage as well as temperature. By analyzing the statistics and features of the RTN, we suggest that this noise is due to the random transition of defects between two metastable states, activated by inelastic scattering with conduction electrons. Our results indicate an important role of defect motions in the $1/f$ noise in CNTs. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4876443]

The switching of resistance between two discrete values, referred to as random telegraph noise,[1] has been observed in a variety of mesoscopic systems such as submicron metal-oxide-semiconductor field-effect-transistors (MOSFETs),[2,3] metallic nanobridges,[4] and small tunnel junctions.[5] Although microscopic details differ from one system to another, the observed switching of resistance is an apparent signature of an underlying two-level fluctuator (TLF), which consists of two energy wells separated by a barrier. The presence of a large number of TLF's, with a wide distribution of fluctuation rates, is generally believed to be responsible for the 1/*f* noise, frequently observed in various materials and systems. 1/*f* noise has also been widely studied in carbon nanotubes,[6–13] and the random telegraph signal has been reported for carbon nanotubes (CNT)-FETs[14–16] and CNT film-silicon Schottky junctions.[17] These random telegraph noises (RTNs) were attributed to charge traps in dielectric materials or in the interface.

In this Letter, we report extensive observations of RTN in individual metallic CNTs. The noise behavior is distinguished from the RTN observed in semiconducting CNT-FETs.[14,15] By analyzing the statistics and features of the current switching, we attribute the RTN to the defect motions between two metastable states. The activation energy for this transition is evaluated from the bias-voltage dependence of the RTN.

Experiments have been carried out on individual metallic single-walled carbon nanotubes (SWNTs) dispersed on Si/SiO_2 substrates. The heavily doped Si was used as a back-gate and the thickness of the oxide layer was 300 nm. For electrical contacts, Ti/Au (5 nm/15 nm) electrodes were deposited on SWNTs using conventional e-beam lithography (Figure 1(c)). Low temperature measurements were performed both in a Janis variable temperature cryogenic system and in a simple liquid He bath. The samples were biased at a constant voltage and the current fluctuations were monitored with either a preamplifier (Ithaco 1211) or a semiconductor characterization system (Keithley 4200). In general, the RTN can be characterized by three parameters, namely the RTN amplitude (ΔI_{ds}) and the mean lifetimes of the high-current state (τ_{high}) and the low-current state (τ_{low}). To obtain reasonable statistical values of these parameters, 5000 to 20 000 current points were registered for a fixed drain-source bias-voltage (V_{ds}). The observation window of τ_{high}, τ_{low} lies between 0.1 s and 1000 s.

In Figs. 1 and 2, we present typical results of two-probe measurements from a representative sample. Figure 1(a) shows time-traces of the drain-source currents (I_{ds}) for five different V_{ds} at $T = 4.2$ K. Current switching between two discrete values is clearly observable in a particular range of V_{ds}, $75 \leq V_{\mathrm{ds}} \leq 180$ mV, and the magnitude of the current fluctuation reaches 30% of the total current. The fluctuation rate becomes faster with increasing V_{ds} and the switching becomes faster than the experimental bandwidth for $V_{\mathrm{ds}} \geq 180$ mV. Values of τ_{high} (•) and τ_{low} (◇), obtained from nine different V_{ds}, are shown in Fig. 1(b). It demonstrates that the τ_{high} and τ_{low} increase exponentially with respect to the inverse V_{ds}. To investigate the effect of gate-voltage (V_g) on the RTN, we checked the current fluctuation as we swept V_g by 20 μV/s in the range of 1 V while keeping $V_{\mathrm{ds}} = 100$ mV. Figure 2(a) shows the measured currents as a function of gate-voltage. The two current levels are clearly distinguishable in the Coulomb oscillations. In Fig. 2(b), the noise amplitude ΔI_{ds} was estimated by taking the difference of the two discrete current-curves in Fig. 2(a). The peak positions of ΔI_{ds} match with those of I_{ds}. The result is consistent with the reported 1/*f* noise characteristics of a SWNT single-electron-transistor (SET),[9] where peaks of both the current and the current noise coincide.

What is the origin of the RTN we have observed in metallic SWNTs? At first, we checked the effect of tunnel conductance fluctuations across the contact barrier, which can possibly cause the RTN, assuming two kinds of contact configurations with different tunnel barriers. To test this, a four-probe measurement was introduced with the electrode configuration shown in Fig. 1(c). We simultaneously measured the RTN in both four- and two-probe configurations, i.e.,

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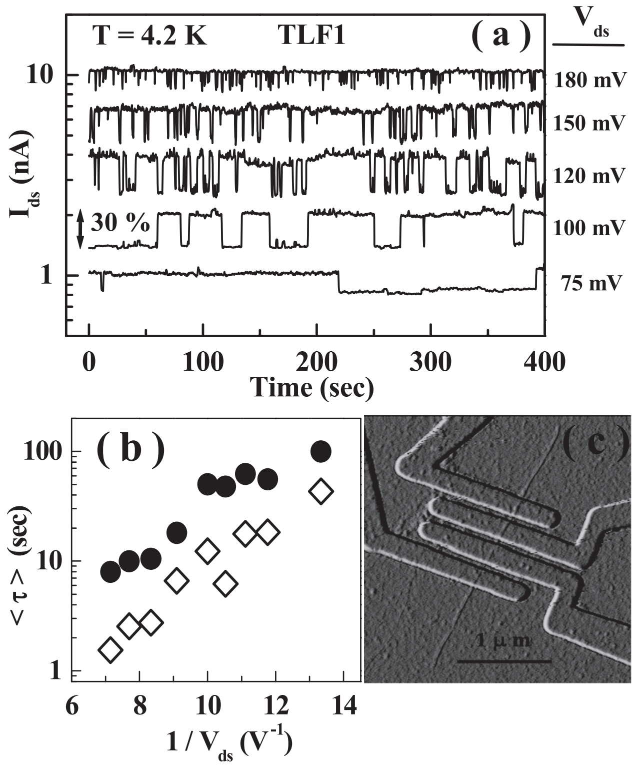

FIG. 1. Random telegraph noise observed in a metallic SWNT at $T = 4.2$ K. (a) Time-traces of currents for five different V_{ds}. Fluctuation rate becomes faster with increasing V_{ds}. The magnitude of current fluctuation reaches 30% of total current. (b) Exponential dependence of mean lifetimes on inverse V_{ds}: τ_{high} [•] and τ_{low} [◇]. (c) Typical tapping-mode atomic force microscope image of SWNT with Ti/Au electrodes on it.

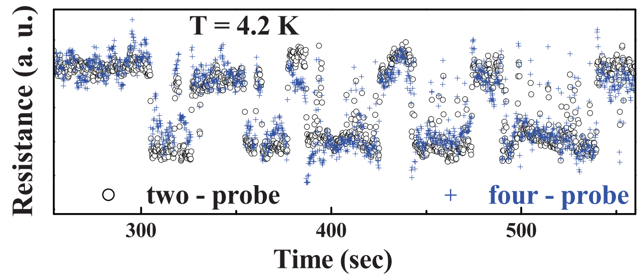

FIG. 3. Resistance traces from four- and two-probe measurements in arbitrary units. The two traces match each other well, proving that the RTN is not due to the contact barriers. For eye convenience, both resistance traces, which show different values, are shifted into the same place.

measuring the I_{ds} and V_{ds} between the outer two electrodes (two-probe) and at the same time measuring the voltage drop between the inner two electrodes (four-probe) of the same sample. Figure 3 shows that both the two- and four-probe resistance switch at the same time, which rules out the role of contact barriers in the RTN.

As a second candidate, we can possibly think about the effect of charge traps in dielectric materials which could explain the RTN in MOSFETs[2,3] and CNT-FETs,[14–16] since

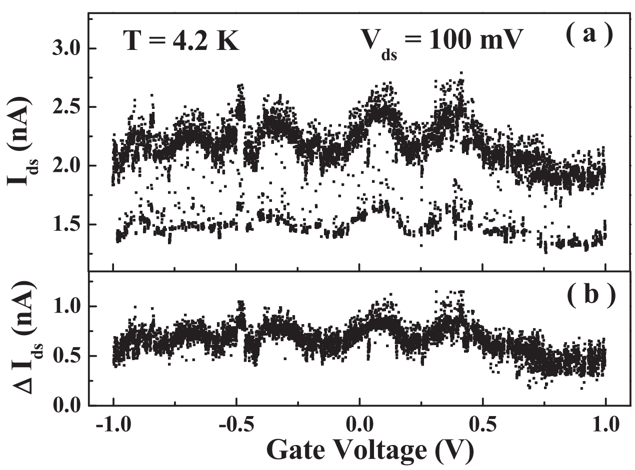

FIG. 2. (a) Drain current as a function of gate-voltage at $T = 4.2$ K while keeping $V_{ds} = 100$ mV. Two discrete current levels are clearly observed in Coulomb oscillations. (b) RTN amplitude (ΔI_{ds}) calculated from Fig. 2(a). ΔI_{ds} shows identical peaked features with I_{ds} presenting maximum noise amplitude at Coulomb conductance peaks.

our experiments have been performed for similar FET structures. However, our results of the RTN in metallic SWNTs are different from those observed in the semiconductors. The same experiment as in Fig. 2(a), performed on a submicron MOSFET in the Coulomb-blockade regime at $T = 4.2$ K, showed two discrete I_{ds}-V_g curves that exhibited the same Coulomb oscillations but were shifted relative to one another along the horizontal axis (V_g).[18] This is because the trapped charge affects the potential of the dot. In our RTN data, however, no horizontal shift is observed as shown in Fig. 2(a). Furthermore, the noise peaks, shown in Fig. 2(b), occur at the zero-gain points, ($\partial I_{ds}/\partial V_g = 0$), where the current is a maximum. If the noise is caused by charge fluctuations, the noise peak should occur at the point of maximum gain, that is, at V_g where I_{ds} is most sensitive to slight fluctuations in gate-voltage.[7,19] Second, τ_{high} and τ_{low} showed no gate-voltage dependence in the range of $V_g = -16$ to 16 V (data not shown). However, a negatively charged trap in an oxide layer is more likely to emit its charge at $V_g \ll 0$ and to maintain it at $V_g \gg 0$. Note that the RTNs in CNT-FETs are observed only in a limited range of the gate-voltage.[14,15] Therefore, the lack of a gate-voltage dependence of τ_{high} and τ_{low} indicates that the RTN is not due to charge fluctuations. Finally, to rule out the effect of traps in the substrate, we prepared a SWNT suspended over the SiO_2 substrate.[20] The RTN still appeared in the suspended SWNT at $T = 1.8$ K (data not shown). Therefore, we conclude that it is necessary to consider another source of the RTN.

Regarding the RTN to be due to intrinsic fluctuations, we now turn our attention to the defects in metallic SWNTs. Considering the high current density ($\sim 10^6$ A/cm^2 at 10 nA) flowing through the surface of a 1 nm-sized carbon tube, a defect in a SWNT could transfer between two metastable positions, activated by inelastic scattering with conduction electrons. The reversible motion of a defect, inducing different electrical properties at each metastable position, could produce the observed telegraphic current fluctuations. We note that RTN in metallic nanobridges has been successfully explained in terms of similar defect motion.[4,21–24] This noise mechanism is consistent with our typical observation of electromigration of defects, which appears as an irreversible current change in time as V_{ds} is further increased.

For the analysis of our results, we adopt the model[21,23] used to describe RTN in metallic nanobridges. The temperature of a defect is usually identical to the lattice temperature. However, in CNTs and metallic nanobridges, the defect temperature T_d is expected to be much higher than the lattice temperature because of the inelastic scattering with conduction electrons as well as the poor energy relaxation to the lattice. With T_d depending on the bias voltage, the model could explain the exponential dependence of the mean lifetimes as a function of V_{ds}^{-1}, observed at large bias-voltages.[21,23,24] Note that we found a similar dependence in Fig. 1(b). Following the approach of Ref. 21, where they calculated T_d in equilibrium with ballistic electrons (treating the defect as a harmonic oscillator), Holweg *et al.* derived the relation $k_B T_d = \alpha e|V_{ds}|$ with $\alpha = 5/16$ for high bias-voltage and low lattice temperature.[23] With a modification term due to the electromigration force, the thermally activated behavior of the mean lifetime τ either in the high- or low-current state was expressed by

$$\tau = \tau_0 \exp\left(\frac{E_B - \zeta V_{ds}}{\alpha e|V_{ds}|}\right),$$

with τ_0 the attempt time, E_B the activation energy, and ζ the electromigration parameter. From the slope of Fig. 1(b), the activation energy E_B of TLF1 in Fig. 1(a) is estimated (with $\alpha = 5/16$) to be 140 meV for τ_{high} and 160 meV for τ_{low}. However, here we point out that for some TLF, the rate becomes independent of V_{ds} at low bias-voltage as shown in Fig. 4. Also, the temperature dependence of the RTN, displayed in the inset of Fig. 4, shows that the fluctuation rate is nearly independent of temperature at $T \leq 20$ K, indicating that tunnelling between the two metastable states, rather than thermal activation, is dominant in this temperature range. Based on these observations, we assume that $T_d = \alpha e|V_{ds}|/k_B$ is equal to 20 K at $V_{ds}^{-1} = 19.5\ \mathrm{V}^{-1}$ where the fluctuation rate becomes saturated at low bias-voltage. Thus, we obtain $\alpha \sim 0.034$ for the TLF2 in Fig. 4. This value is an order of magnitude smaller than $\alpha = 5/16$ suggested by the theory for metallic nanobridges. The voltage drop at the contact between the SWNT and the electrodes could be responsible for the reduced value of α, together with the effect of energy relaxation to the lattice, which is not accounted for in the above theory. Also, the small α parameter reflects our diffusive SWNT device, allowing an electron to scatter off defects several times while traversing the tube.

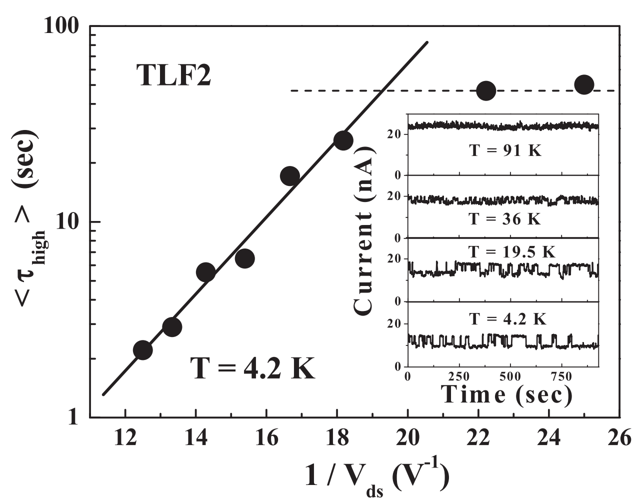

FIG. 4. τ_{high} obtained from eight different V_{ds} for a SWNT at $T = 4.2$ K. While again the exponential dependence on inverse V_{ds} is observed, the fluctuation rate becomes independent of V_{ds} at low bias-voltage. Inset displays the temperature dependence of the RTN measured at $V_{ds} = 50$ mV. Fluctuation rate is nearly independent of temperature for $T \leq 20$ K, indicating that tunnelling between the two metastable states is dominant in this temperature range.

In Table I, the magnitude of the current fluctuation and the estimated activation energy (with experimentally determined α) are summarized for three different TLF's. The measured $\Delta I_{ds}/I_{ds} \sim 0.1$–$0.3$ is two to four orders of magnitude larger than that of the metallic nanobridges (diameter $\sim$10 nm).[4,21–23] This can be attributed to the much narrower current path in the SWNTs. In fact, for atomic-scale metal-constriction, the magnitude of the fluctuation can be as large as the total conductance.[24] The small activation energy of 15–24 meV is a reflection of our measurement temperature ($T = 4.2$ K), and it is comparable to those of the metallic nanobridges measured at the same temperature. In most systems where RTN was found, the measured activation energy was a strong function of the temperature.[2,22] This is because only the TLF for which the activation energy corresponds to the measurement temperature can be observable as RTN in the experimental bandwidth. At higher temperatures, the RTN was often observed with several TLF's acting at the same time. In that case, the frequency dependence of the noise became close to the $1/f$ spectrum. If we regard the $1/f$ noise as a superposition of such TLF's, our results indicate an important role of defect motions in the $1/f$ noise observed in the CNTs.[6–12] In many CNT devices, prepared on dielectric substrates, charge traps in the vicinity of CNTs are expected to play a role in the $1/f$ noise. However, the deviation from the typical gain dependence of the $1/f$ noise, reported for CNT-SETs,[7,9] cannot be explained by the charge fluctuations alone and instead can be understood by invoking a noise mechanism due to the defect motions. Also, in the frequency domain, the current power spectral density of the RTN is a Lorentzian given by[26]

$$\frac{S_I(f)}{I_{ds}^2} = \frac{4(\Delta I_{ds}/I_{ds})^2}{(\tau_{high} + \tau_{low})[(1/\tau_{high} + 1/\tau_{low})^2 + (2\pi f)^2]}.$$

With the $1/f^2$ tail of the Lorentzian, we note that the $1/f^2$ dependence of the noise (instead of $1/f$) observed in free-standing CNTs[8,11] can be interpreted as due to the presence of RTN, generated by defect motions.

Large RTN amplitude observed for metallic SWNTs suggests the possibility to use RTN measurements as a sensitive probe for characterizing the defects in nanotubes. Also, it is remarkable that, increasing the number of defects on the tubes by Cs ion irradiation, we could sometimes observe more

TABLE I. The magnitude of current fluctuation and the activation energy summarized for three different TLF's observed in metallic SWNTs.[25]

Fluctuator	$\Delta I_{ds}/I_{ds}$	Current State	E_B (meV)	α
TLF1	0.3	high	20.7	
		low	24	
TLF2	0.33	high	15.3	0.034
		low	15.6	
TLF3	0.1	low	15.4	0.058

current levels appearing in the time traces, which resulted in overall higher resistance fluctuations. With further investigations, RTN approach could be developed into a comparative diagnostic to grade differently prepared nanotubes.

In summary, we have investigated random telegraph noise observed in individual metallic SWNTs. Reversible motion of a defect, activated by inelastic scattering with conduction electrons, is suggested to be responsible for the observed RTN. Regarding the $1/f$ noise as a superposition of two-level current switchings, our results imply an important role of defect motions as a source of the $1/f$ noise for the CNTs.

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